E/N IN TRANSIENT GAS DISCHARGES

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SUMMARY

Current and voltage waveforms in transient gas discharges have been analyzed. A pulse transmission line system was employed to overvolt a test gap filled with various electron attaching gases. The reduced electrical field measured at the zero current growth portion of the discharge was found to be slightly lower than dc or ac breakdown fields for most of the gases studied. The transient discharge technique was also found useful in the determination of plasma resistance during the initial stage of constant current, the phase most likely to exhibit diffuse glow discharge character.

INTRODUCTION

Processes which occur during the formation of highly overvolted electrical discharges in molecular gases effect the gases' electrical properties. The reduced field at the zero current growth level in transient discharges in attaching gases differs, for instance, from that predicted for the unperturbed gas. It may affect the electron temperature and tend to decrease the plasma resistance. This difference, though typically not large, may become important in the application of transient discharges to pumping gas lasers and to fast switching techniques.

In this paper we present transient current waveforms for several attaching gases (SF_6, O_2, CCl_2F_2, $CClF_3$, CF_4, CCl_4, $SiCl_4$) obtained under a variety of initial conditions. We have measured the reduced field value $(E/N)_s$, at which the current growth reaches zero. This field strength is then compared with the reduced dc breakdown field strength $(E/N)_{dc}$, and with the field at which the electron collisional ionization rate is balanced by the electron attachment rate $(E/N)_c$. Finally, we analyze the plasma resistance measured during the period of zero current growth, the phase which is most likely to have diffuse glow discharge character.

EXPERIMENT

The experimental setup used in our investigations of fast breakdown under highly overvolted conditions is shown schematically in Figure 1. A 50Ω transmission line system delivers a 45 ns wide, almost rectangular pulse of 20 kV to 30 kV amplitude to the test gap. Gap spacing may be varied from 0.25 cm to 1.75 cm between 4.4 cm dia. plane parallel stainless steel electrodes. Gas pressures have ranged from 30 torr to 1 atm, though most of the data for CCl_4 and $SiCl_4$ vapors have been taken only at the pressures of 30 torr and of 80 torr, respectively. These pressures correspond to the vapor pressures in equilibrium with the liquid phase at 0°C. The test chamber was pumped to 10^{-2} torr before backfilling with the gas to be studied. The chamber was refilled after each series of approximately 10 to 20 discharges.

The statistical breakdown lag time was minimized by initial electrons provided by means of a pulsed UV light source. Current waveforms were monitored with a capacitive divider and recorded by means of a fast transient digitizer. Subnanosecond time resolution and a high level of reproducibility have been achieved.

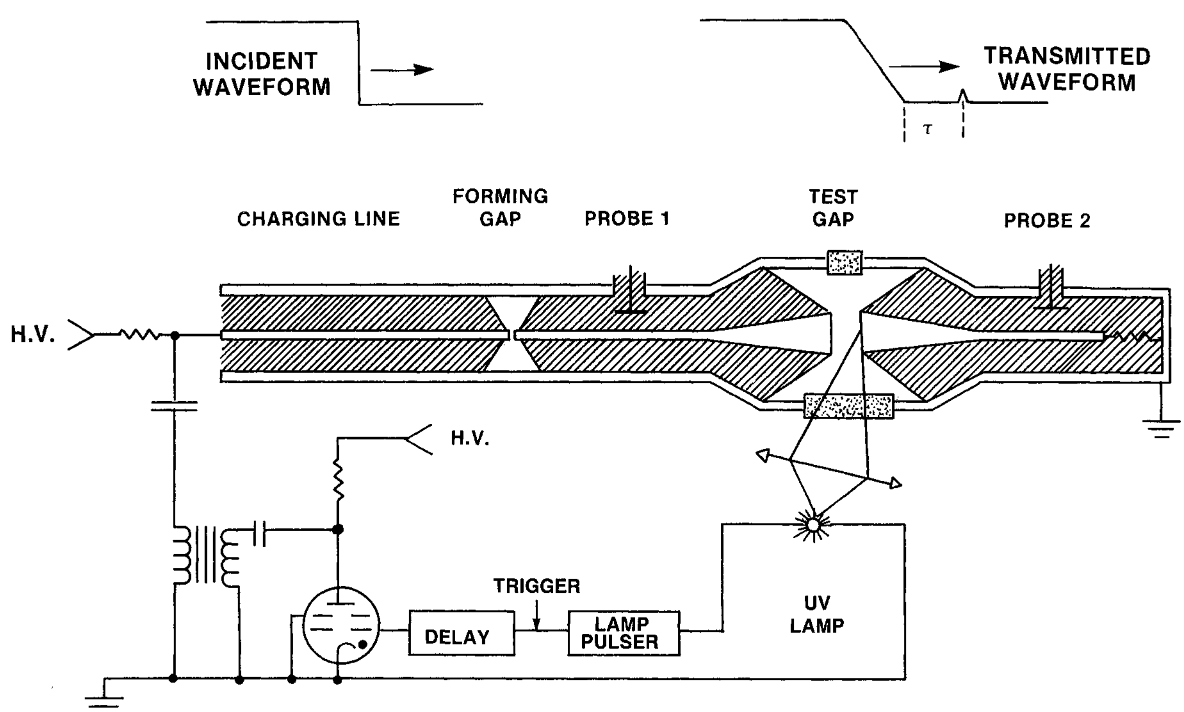

Figure 1. Schematic diagram of the pulsed transmission line system. The circuit synchronizes a UV flash lamp and the forming gap which launches the test pulse.

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RESULTS

Current waveforms obtained in SF_6 at two different pressures are shown in Figure 2. Discharge currents, following a formative period, rise rapidly to the value I_S, at which the total electron production rate is balanced by the electron loss rate. The current remains at this constant level for a time which varies with pressure. The value of reduced field strength, $(E/N)_S$, at the current level I_S may be obtained from the circuit equation for the transmission line system:[1]

$$(E/N)_s = E_o/N - 2ZI_s/dN \qquad (1)$$

where:

$E_o = V_o/d$ is the applied voltage waveform $V_o(t)$, divided by the electrode separation, d;

$V_o(t)$ is represented in current units in Figure 2 and is labeled $V_o/2Z$;

Z is the transmission line impedance; and

N is the molecular number density.

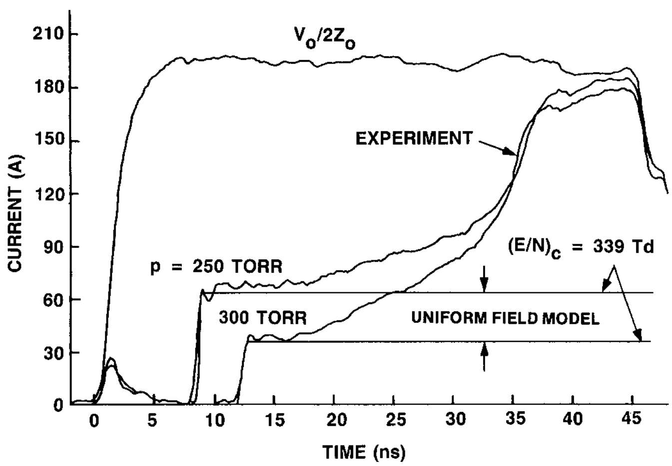

Figure 2. Current waveforms in SF_6 at p=250 torr and p=300 torr; electrode separation d=0.5 cm and amplitude of applied voltage V_o=20 kV. The incident voltage waveform represented in current units is labeled $V_o/2Z$. Numerical results are labeled "Uniform Field Model."

During early phases of the discharge, characterized by the persistent value $(E/N)_S$, diffuse glow discharges have been observed in a number of gases.[2-5] The data reported here for SF_6 appear to be consistent with these results. Good agreement between experimentally determined values of I_S and those calculated on the basis of a uniform field discharge model[1] has been observed as illustrated in Figure 2. This indicates that the field may indeed be uniform and diffuse glow discharge conditions may prevail during this phase. Similar conclusions may be reached through the analysis of current waveforms measured in other electronegative gases. Some typical results are presented in Figures 3 through 6.

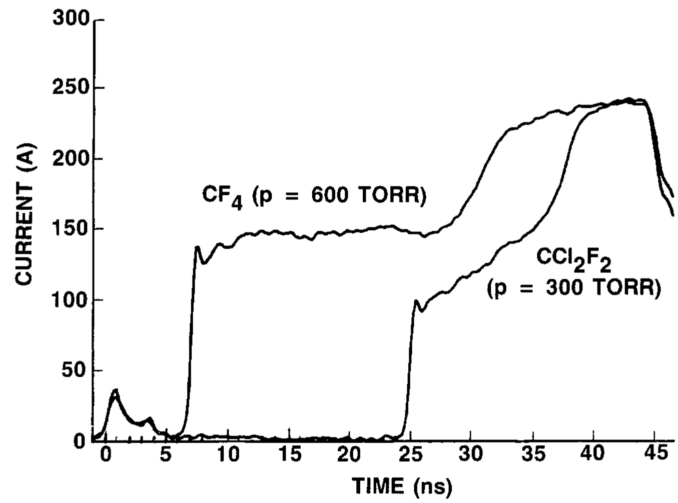

Figure 3. Current waveforms in CF_4 (p=600 torr) and CCl_2F_2 (p=300 torr). V_o=25 kV, and d=0.5 cm.

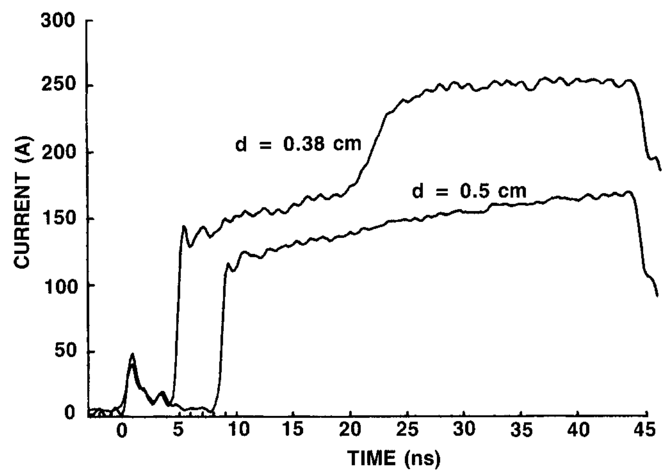

Figure 4. Current waveforms in $CClF_3$ (Freon 13) at d=0.38 cm and d=0.5 cm, pressure p=500 torr and V_o=25 kV.

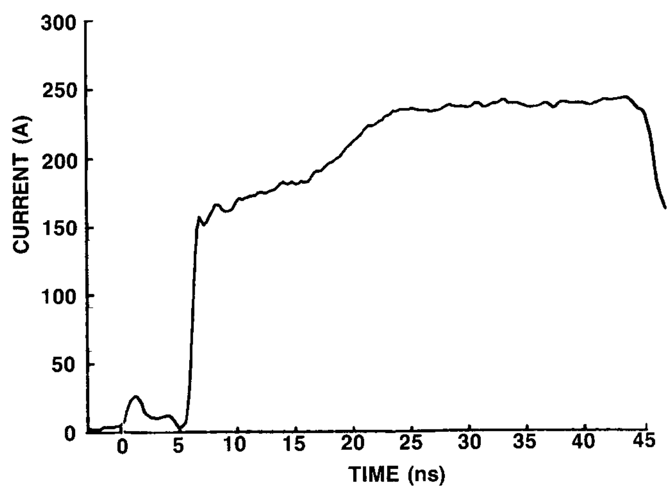

Figure 5. Current waveform in $SiCl_4$ at a cold spot temperature T=0°C (p=80 torr), d=0.75 cm and V_o=25 kV.

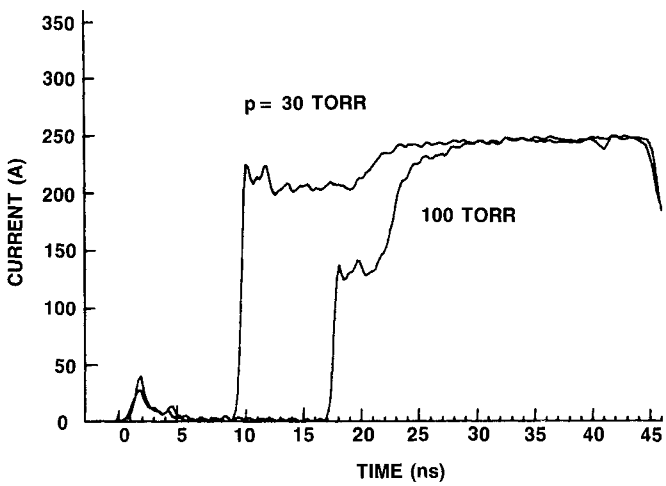

Figure 6. Current waveforms in CCl_4 at cold spot temperature T=0°C (p=30 torr) and T=23°C (p=100 torr), d=0.5 cm and V_0=25 kV.

The constant current portion of the discharge is followed by a gradual increase in current and a subsequent steep rise to a value limited by the impedance of the external circuit. In the final stage of the discharge, the plasma resistance reaches low values characteristic of arc conditions. The current rise from I_s to the circuit limited value therefore represents a transition from glow to arc discharge conditions.[2-6] It is noteworthy that such a clear illustration of this transition in electronegative gases on a nanosecond time scale as shown in Figures 2 through 6 seems to be rather unique and to the best of our knowledge has been demonstrated previously only in SF_6.[5,6] In contrast, the current observed in non-attaching nitrogen is seen to rise, in our experiment, smoothly towards the circuit limited value.[1]

In Figure 3 current waveforms in CCl_2F_2 (Freon 12) and CF_4 (Freon 14) are compared. CCl_2F_2, a much stronger attacher, has an $(E/N)_s$ value higher than that of CF_4. This can be readily seen from Figure 3, where comparable values of I_s have been reached even though the incident reduced fields differ by a factor of two. Since all the gases studied do not have an appreciable flat section of the current waveform (e.g., CCl_2F_2 in Figure 3), I_s has been taken experimentally as the average between the first maximum and minimum of the current waveform after breakdown. This represents the first point at which current growth equals zero and is a feature found in all cases of interest. Although the flat section of the CF_4 waveform lies slightly above this value, glow conditions may still prevail for this region.

A long gradual current rise from I_s is observed in $CClF_3$ (Freon 13), as shown in Figure 4. Here waveforms taken at two different electrode separations, d = 0.5 cm and d = 0.38 cm, are presented. In the case with a lower initial field (d = 0.5 cm), the full transition to an arc stage does not occur within the 45 ns pulse width.

A current waveform in silicon tetrachloride ($SiCl_4$) vapor at a cold spot temperature of 0°C (p = 80 torr) is shown in Figure 5. The incident reduced field for measurements in $SiCl_4$ was controlled by the electrode separation and the amplitude of the applied voltage only. Although $SiCl_4$ has a high dielectric strength, it exhibits a rather slow glow-to-arc transition.

Typical current waveforms in carbon tetrachloride (CCl_4) at two cold spot temperatures, 0°C and 23°C (p = 30 torr and 100 torr), are compared in Figure 6. CCl_4 has the highest dielectric strength of the compounds studied and displays a very rapid current rise to I_s. The current then falls slightly from I_s to a flat portion probably representing a glow stage. The flat portion of the current waveform appearing at a value lower than I_s may be due to transient non-equilibrium conditions in the discharge.

DISCUSSION

Current waveforms such as those illustrated in Figures 2 through 6 were used to provide values of I_s from which $(E/N)_s$ could be calculated with Eq (1). The results summarized in Table 1 were derived from repeated experiments representing, typically, 25 different combinations of the initial parameters V_0, d and N to yield an average value and the standard deviation as tabulated. The standard deviations do not include the uncertainties in the measurement of I_s. The wavy character of the current waveforms at this point is related to the rapid decrease in the net ionization rate to zero when the field collapses from a highly overvolted state to the breakdown value, and provides the main source of error in individual I_s determinations.

TABLE 1

REDUCED FIELD AT BREAKDOWN FOR VARIOUS GASES AND VAPORS

Gas/ Vapor	$(E/N)_s$ (Td)	E_o/N (Td)	$(E/N)_c$ (Td)	References	$(E/N)_{dc}$ (Td)
CCl_4	720±60	1370-8300	950	7,8	823
$SiCl_4$	450±45	540-3110	-	-	-
SF_6	336±10	390-2070	362	9	352
			355-360	7,8,10, 11	
CCl_2F_2	312±14	410-2490	345-385	12-17	358
$CClF_3$	179± 9	250-1560	-	-	192
CF_4	104± 5	160- 620	135-149	18-22	149
O_2	85± 8	140- 830	108-119	23-28	116

The gases and vapors cited in Table 1 are listed in order of decreasing values of $(E/N)_s$. The third column in the table indicates the range of applied reduced field, E_0/N, which was used for each gas. The fourth column of Table 1 summarizes published values of reduced field, $(E/N)_c$, for which the ionization coefficient α and attachment coefficient β are equal.[7-28] The range in values of (E/N) reflects the spread in these data. The value of $(E/N)_c$ = 362 Td obtained in Ref. 10 for SF_6 (corrected for detachment is presently thought to be the most reliable.[29,30] No recent data were found for ionization and attachment coefficients in CCl_4 and $SiCl_4$, and the available data for $SiCl_4$ do not contain the intersection of the two coefficients.[7,8] The value of $(E/N)_s$ = 450 ± 45 Td obtained in our measurements in $SiCl_4$ may be viewed as an approximation for $(E/N)_{dc}$ or the dielectric breakdown strength $(E/N)_c$. The last column of Table 1 presents literature values[31] for the dc breakdown field strength.

Our measurements of $(E/N)_S$ produce values which are consistently smaller than the reduced field, $(E/N)_C$, at which $\alpha = \beta$, and lower than the breakdown field strength. The value $(E/N)_C$ takes into account only electron production by impact ionization and electron loss by attachment (except that mentioned above for SF_6 which is a detachment corrected value). In our discharge measurement, however, there are additional means of electron production; e.g., enhanced ionization due to a local space charge field.[32] Since this process tends to increase the ionization rate, the observed value of $(E/N)_S$ is expected to be smaller than $(E/N)_C$. Similarly, $(E/N)_S$ is expected to be smaller than $(E/N)_{dc}$ because this additional process is not important at low values of applied field. One may also expect that the fast change from a high voltage across the gap during the formative phase to a much lower value during the discharge creates temporal nonequilibrium. This may cause further deviation from a simplified discharge model based on equilibrium ionization and attachment rates and drift velocity, consequently yielding a higher level of ionization than expected. The initial current rise beyond and settling to a constant level observed in CCl_4 (see Figure 6) may be related to this temporal nonequilibrium. The effects of nonequilibrium between the external field and electron energy distribution as well as the question of applicability of transport coefficients in describing transient discharge behavior require further study.

The above measurements of $(E/N)_S$ can be used to calculate the plasma resistance during the constant current discharge phase. Equation (1) may be rewritten in the following manner:

$$R_s = V_s/I_s = 2Z\ [1/(1-1/\chi_s) - 1] \tag{2}$$

where:

R_s is the plasma resistance, and

$\chi_s = (E_o/N)/(E/N)_s$ is the ratio of incident field to $(E/N)_s$

The plasma resistance, R_S, as a function of relative incident field, is shown in Figure 7 for two different transmission line impedance values, $Z = 50\Omega$ and $Z = 5\Omega$. One may use values of $(E/N)_S$ from Table 1

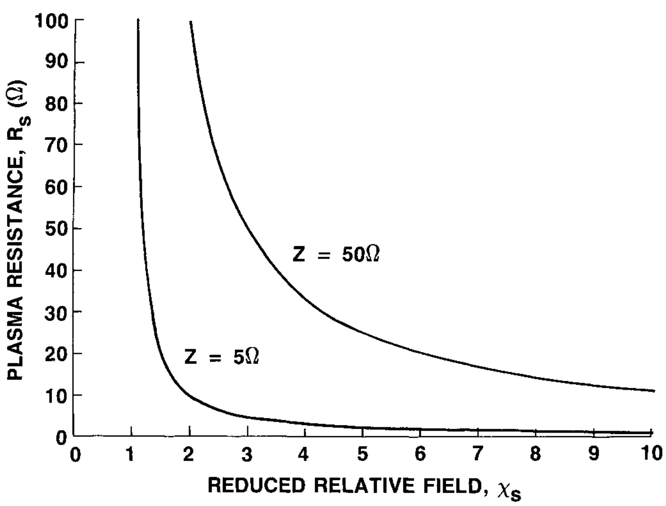

Figure 7. Plasma resistance, R_S, vs relative reduced field $\chi_S = (E_O/N)/(E/N)_S$ for transmission line system with impedances Z=50Ω and Z=5Ω.

and find from Figure 7 the corresponding resistance for the chosen gas and incident reduced field value, E_O/N. In gases with high dielectric strength [characterized by high values of $(E/N)_C$], low plasma resistance values may be achieved only at high field strength or low line impedance. This demonstrates the effect of the circuit impedance on plasma resistance and current in the glow phase. It should also be noted that for similar initial conditions, lower values of R_S are obtained in transient discharges than those predicted for dc breakdown.

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